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This report describes activities in Time and Frequency Metrology pursued since the last meeting of the CCTF in 2012.

Content

1- Primary frequency standards

LNE-SYRTE currently operates 3 primary cold cesium clocks which regularly contribute to TAI: FO1 is a cesium fountain (TAI since 1995), FOM is a transportable cesium fountain (TAI since 2002) and FO2 is a double fountain operating with cesium (TAI since 2002) and rubidium (since 2012 published in *Circular T* as secondary frequency standard and since July 2013 included in the steering of TAI). The operation of FO2 simultaneously with cesium and rubidium atoms started in 2009.

LNE-SYRTE is also leading the scientific development of a cold atom primary standard for space, called PHARAO. The development of this program is managed by the French space agency CNES. The PHARAO clock is a major component of the payload of the *Atomic Clock Ensemble in Space* (ACES) mission of the European space agency ESA. The PHARAO flight model was delivered in July 2014.

Fountain clocks

In nominal operation, the 3 fountains use the same reference signal provided by a cryogenic sapphire oscillator (CSO) phase locked to a hydrogen maser in order to reach the quantum projection noise limit. The relative frequency instabilities are routinely $\sigma_y(\tau) \sim 5\times10^{-14}\ \tau^{-1/2}$ for FO1, FO2-Cs and FO2-Rb. It is about $8\times10^{-14}\ \tau^{-1/2}$ for FOM. These instabilities result from the combination of low and high atomic density operations required for the real time extrapolation of the cold collisions frequency shift and correspond to the quantum projection noise. The magnetic field and the temperature around the interrogation zone are measured every ~1 hour in order to estimate the corresponding frequency shifts of the clock transition. The distributed cavity phase shift is verified from time to time with differential measurements alternating the cavity feeds.

New measurements of the Stark effect have been performed using FO1 when applying a static electric field on the atoms during the interrogation period. The tensor effect was also measured using RF spectroscopy of the $m_f \neq 0$ Zeeman sublevels. The measurement results are in agreement with the theory of Angstmann et al, Phys. Rev. A, **74**, 023405 (2006), and Beloy et al, Phys. Rev. Lett. **97**, 040801 (2006).

Preliminary tests of the effect of background gas collisions, according to Gibble, Phys. Rev. Lett. 110, 18802 (2013) have been undertaken in FO2 and will be pursued.

We have also tested a new method for evaluating the cold collisions frequency shift proposed by Gibble ("Fountain clock accuracy'', *Proceedings of the 2012 European Frequency and Time Forum*) using FO2-Rb and FO1. This method, which consists in varying the state selection microwave frequency instead of the amplitude, is less sensitive to fluctuations in the atomic cloud shape between high and low density. This method will also be used for the space clock PHARAO.

The mobile fountain FOM was in operation at CNES Toulouse between June 2012 and July 2014 for tests of the PHARAO space clock flight model.

An automatic fountain data processing was implemented in order to provide frequency calibrations of the reference maser in almost real time with an uncertainty of 10^{-15} or below. This allowed a major improvement of the French timescale UTC(OP) that is based on a frequency steered hydrogen maser, remaining a few ns close to UTC, since October 2012.

New absolute frequency measurements, referenced to our fountains, have been performed on our two strontium optical clocks and our mercury clock.

The following table gives the accuracy budget of the LNE-SYRTE fountains:

	FO1	**FO2-Cs**	**FOM**	**FO2-Rb**
Quadratic Zeeman Shift	-1274.5 ± 0.4	-1915.9 ± 0.3	-305.6 ± 1.2	-3465.5 ± 0.7
BlackBody Radiation	172.6 ± 0.6	168.0 ± 0.6	165.6 ± 0.6	122.8 ± 1.3
Collisions and Cavity Pulling	70.5 ± 1.4	112.0 ± 1.2	28.6 ± 5.0	2.0 ± 2.5
Distributed Cavity Phase Shift	-1.0 ± 2.7	-0.9 ± 0.9	-0.7 ± 1.6	0.4 ± 1.0
Spectral Purity and Leakage	<1.0	<0.5	<4.0	<0.5
Ramsey & Rabi pulling	<1.0	<0.1	<0.1	<0.1
Microwave Lensing	-0.7 ± 0.7	-0.7 ± 0.7	-0.9 ± 0.9	-0.7 ± 0.7
Second-Order Doppler Shift	<0.1	<0.1	<0.1	<0.1
Background Collisions	<0.3	<1.0	<1.0	<1.0
Total without Red Shift	1033.1 ± 3.5	-1637.5 ± 2.1	-113.0 ± 6.9	-3341. ± 3.3
Red Shift	-69.3 ± 1.0	-65.4 ± 1.0	-68.7 ± 1.0	-65.4 ± 1.0
Total with Red Shift	-1102.4 ± 3.7	-1702.9±2.3	-181.7 ± 6.9	-3406.4 ± 3.5

Table 1: Systematic fractional frequency corrections and uncertainties for FO1, FO2-Cs, FOM and FO2-Rb, in units of 10^{-16}, as published in J. Guéna, et al, IEEE Trans. Ultra. Ferr. Freq. Contr. 59 (3), 391-410 (2012).

▪ Contributions to TAI with primary and secondary frequency standards

From January 2012 to July 2015, the LNE-SYRTE primary standards, FO1, FO2-Cs and FOM provided 28, 44 and 6 calibrations reports to the BIPM, respectively, to contribute to the steering of TAI (see Figure 1). This corresponds to measurement durations of 690, 1140 and 130 days, respectively. The mobile fountain FOM, in operation at CNES Toulouse between June 2012 and July 2014 for tests of the PHARAO space clock flight model, was not connected to the reference maser at Observatoire de Paris.

Based on comparisons of FO2-Rb against FO2-Cs and FOM, performed between January and August 2012, a new value for the secondary representation (see J. Guéna, et al, Metrologia 51, 108 (2014)) of the second based on the rubidium hyperfine splitting frequency was proposed at the 19th CCTF. This new value was adopted by the CIPM at its 102nd meeting in June 2013.

FO2-Rb calibration reports were regularly sent to BIPM over the past 3 years and included in *Circular T*: 46 calibration values were transmitted, corresponding to a measurement duration of 1090 days. The first 18 ones were referenced to the 2004 previous definition of the secondary representation of the second and the following calibrations, to the new definition. Initially the FO2-Rb data published in *Circular T* had no weight in the steering of TAI. The participation to the steering of TAI started in July 2013. A frequency comparison between FO2-Cs and FO2-Rb performed over September 2012 to July 2015 shows a difference of 1.3×10^{-16} with a statistical uncertainty of 7×10^{-17} fully in agreement with the accuracy budgets of the fountains. This confirms the current recommended value of the Rb hyperfine splitting frequency.

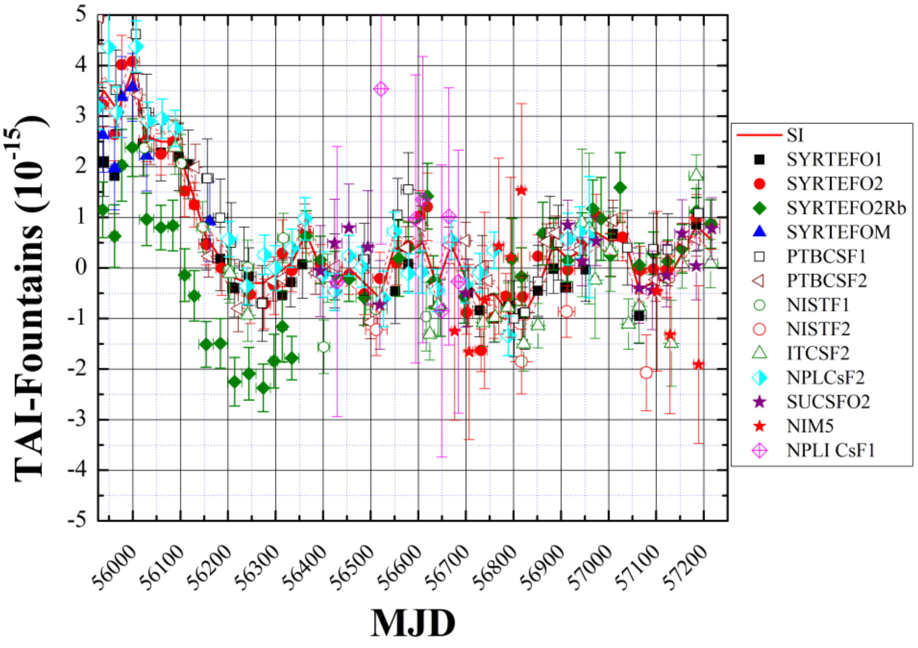

Figure 1: Contributions to TAI from all PFS worldwide over January 2012 – July 2015, including the evaluations from the Rb secondary representation.

▪ The PHARAO/ACES space mission

LNE-SYRTE participates to the space mission PHARAO/ACES of the European Space Agency. It is the Principal investigator in the development of the first primary frequency standard for space operation: PHARAO developed by CNES. LNE-SYRTE is also developing the software for the scientific analysis of the data comparisons between ground and space clocks. During the mission LNE-SYRTE will be a major ground station to fulfill the scientific objectives of the ACES mission.

The flight model of the laser cooled atomic clock PHARAO was delivered and qualified to operate in space. The clock has successfully passed the environment and the performances tests. In space, we foresee a frequency stability of $1.1\times10^{-13}\tau^{-1/2}$ and a frequency accuracy of 1.2×10^{-16}. The clock was delivered to the European Space Agency on July 2014 to start the assembly of the ACES payload.

The scientific data analysis software including simulation tools has been achieved and tested. It is under validation by using ACES type data packages.

The ACES ground station at Observatoire de Paris is due for completion by the spring 2016. Works include secure power supply for the clocks, installation of the ACES microwave link radome and calibration of the reference signals.

2- Time scales

UTC(OP)

A new method was implemented in October 2012 for the generation of the French time scale UTC(OP). UTC(OP) is realized using a microphase stepper fed by the reference maser of the laboratory. A frequency correction is updated every day to compensate for the maser frequency variations and to maintain UTC(OP) close to UTC. This correction is the sum of two terms: the main term corresponds to the current frequency of the maser as measured by LNE-SYRTE’s atomic fountains. The value is estimated with a linear extrapolation of the data covering the past 20 days to remain robust against possible interruptions of data provision or of the automatic data processing; the second term is a fine steering to maintain UTC(OP) close to UTC, compensating for the frequency and the phase offset between UTC(OP) and UTC. It is updated monthly at the BIPM *Circular T* publication. The steering correction is usually of the order of 10^{-15} or below.

Figure 2 below shows the comparison of three UTC(k) to UTC as published in *Circular T* since the implementation of the new UTC(OP). Over the reported period, UTC(OP) is one of the three best real-time realizations of UTC with UTC(PTB), the pivot of the time transfers for international contributions to TAI, and UTC(USNO), the laboratory providing the largest number of clock data included in EAL computation. The departure between UTC(OP) and UTC remains well below 10 ns, with an rms value of less than 3 ns, which approaches the uncertainty of the time transfer calibrations. This is an improvement by a factor of about 5 compared to the previous realization method of the time scale. On-going instrumental upgrades shall further improve the short-term stability of the time scale and the robustness of the system.

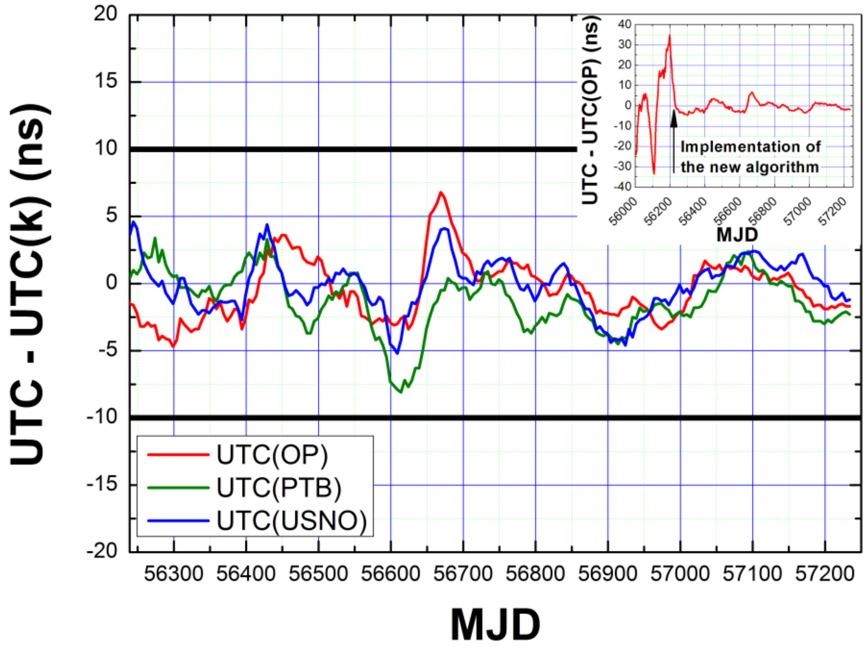

Figure 2: Comparison of UTC(OP), UTC(PTB) and UTC(USNO) with UTC from data published in *Circular T*.

- **TA(F)**

LNE-SYRTE also maintain the French time scale TA(F), which is based on a weighted averaging of about 20 to 25 commercial caesium beam clocks located in some 10 French laboratories, that are daily compared to UTC(OP) using GPS CV. This time scale is calculated monthly before sending clock data to the BIPM to contribute to EAL computation. The time scale algorithm uses the ARIMA method for the weighted averaging of the clock data. The resulting time scale is the frequency steered using the LNE-SYRTE fountains calibrations. With this method, the monthly average frequency of TA(F) is in agreement with that of the SI second within a few 10^{-16} with an rms value of ~10^{-15} as can be analyzed from the data published in the BIPM *Circular T*.

3- Time and frequency transfer

- **GNSS for time and frequency transfer**

Time and frequency transfer

LNE-SYRTE provides daily to BIPM the required GPS RINEX data for the PPP processing part of the TAI/UTC generation and for UTCr generation. In addition, GPS and GLONASS CGGTTS data are forwarded to BIPM too, including data for the computation of UTC – UTC(USNO)_GPS. One of LNE-SYRTE dual-frequency GPS receivers is registered as a permanent IGS operational station called OPMT, which is also part of the French Réseau GPS Permanent (RGP) established by the Institut Géographique National (IGN). The OPMT IGS station main unit is now directly connected to the UTC(OP) signal instead of an intermediate H-maser.

Calibration

LNE-SYRTE, together with Observatoire de la Côte d'Azur (OCA) in Calern (France) and NERC Space Geodetic Facility (SGF) in Herstmonceux (United Kingdom) achieved a GPS relative calibration campaign with specifically designed equipment, which allowed to reach a GPS receiver calibration expanded uncertainty between 2.0 and 3.2 ns (k = 2), and a GPS link calibration expanded uncertainty between 1.5 and 2.1 ns (k = 2). This relative calibration campaign was carried out in parallel with a similar campaign for the Time Transfer by Laser Link (T2L2) between the same stations, which provided an expanded uncertainty below 140 ps (k = 2) for all links. A direct comparison between these two independently calibrated techniques on the three European links lead to difference mean values below 240 ps, which is an unprecedented result. On the other hand, a GNSS signal simulator was used to measure antenna cable delays with GPS signals as input. The comparison of the results with similar measurements made by using a Vector Network Analyzer (VNA) shows a consistency better than 100 ps. Finally, the continuous monitoring of the differences between GPS TAIP3 CV and TWSTFT on the OP-PTB link shows an average drift of about 1 ns/year during the last five years.

▪ Contribution to European GNSS projects

EGNOS

The broadcast value for UTC – ENT (EGNOS Network Time) is obtained through UTC(OP) via a ground station located in OP. The improvement in the UTC(OP) time scale since 2012 has led naturally to an improved access to UTC for EGNOS users.

Galileo

Together with other European NMIs, LNE-SYRTE is contributing to Galileo activities at system level by providing daily GPS CV and TWSTFT data collected against UTC(OP), to be used for the generation of a prediction of UTC aiming at Galileo System Time steering. In addition, in the frame of the current industrial contract dedicated to the Time Validation Facility (TVF), LNE-SYRTE is in charge of the characterization of GPS receiver delays, for receivers located in the participating NMIs or in the Galileo Precise Time Facilities (PTF). Since the start of the current contract, all requirements have been fulfilled on these aspects.

▪ Two-Way Satellite Time and Frequency Transfer

LNE-SYRTE operates two fully independent Ku-band VSAT stations, connected to a common Hydrogen-Maser:

1. A calibrated station at the nanosecond level, equipped with a satellite simulator developed in the laboratory, dedicated to European and Transatlantic two-way networks, providing data according to ITU format for the :
   i-) computation by the BIPM of UTC - UTC(OP) by using the primary two-way link OP-PTB ; over the past three years, a combined uncertainty of 1,3 ns to 1,9 ns on UTC-UTC(OP) is

obtained, as calculated and published by the BIPM and, the deviation between two successive calibration values on the OP-PTB link does not exceeded 300 ps;
ii-) contribution to Galileo activities at system level as described above in this report.

2. A second station used for research and development activities; It is in this context that the work done during the past few years has achieved the following main results:
i-) Fluctuations in the differential delay of the two stations do not exceed 200 ps over a period of one year, a consistent value with respect to the combined uncertainty as published in *Circular T*;
ii-) Setting up an original scientific experience using firstly, the code phase at 20 MChip/s, in the frame of EURAMET/EMRP/ITOC project for which several laboratories and partners are involved including four European NMIs/DIs (INRIM, LNE-SYRTE, NPL and PTB), the stability of the OP-PTB link reached $1x10^{-11}$ at 1 s and $3x10^{-16}$ at 1 d, about an order of magnitude better than the most efficient operational satellite time and frequency transfer techniques and on the other hand, the carrier phase, as part of a collaboration with NICT and PTB, using the satellite dedicated to ITOC, for which the stability of the OP-PTB link achieved $2,5x10^{-13}$ at 1 s and $4x10^{-16}$ at 1 d.

4- Optical clocks

LNE-SYRTE is developing two optical lattice clocks based on strontium and one optical lattice clock based on mercury. Below we summarize the main achievements on these lattice clocks since the 19th CCTF report.

Sr lattice clocks

- The current fractional accuracy budget of the Sr2 clock is 4.1×10^{-17}. The leading source of uncertainty is the black-body radiation shift. We observe no density-dependent frequency shift with a statistical resolution of $1,7\times10^{-17}$.
- We have assembled a new vacuum system for the Sr1 clock for a better mechanical stability and reduced BBR uncertainty. With this new system, we could demonstrate a frequency stability of 1.5×10^{-15} at 1 second between our two strontium clocks. The frequency stability between the each strontium clock and the common clock laser shows a white noise behavior with a 10^{-15} Allan deviation at 1s, and is limited after a few 10s of seconds by the laser flicker noise at 6.5×10^{-16}.
- We have demonstrated 3 long operations of the Sr2 clock, spanning from 1 week to 3 weeks, with a total uptime larger than 80%, including the connection to microwave standards via a fiber-based frequency comb.
- We have repeatedly and consistently measured the absolute frequency of the Sr2 clock transition against the FO1 and FO2 primary standards. The outcome has a total error bar of 2.8×10^{-16}, and is compatible with previously reported measurements.
- We have measured the frequency ratio between the Sr2 and the FO2 Rb standard. The frequency ratio is compatible with the known Cs/Rb frequency ratio and the Sr/Cs frequency reported above.
- We observe reproducible magic wavelength measurements, leading a cancellation of the scalar light shift at 368,554,725 (5) MHz , and observe an agreement between the effective magic wavelengths of the two strontium clocks.
- We have observed repeated frequency shifts of several 10^{-15} when the lattice light is generated by semi-conductor sources. This frequency shift is time dependent and shift dependent. In order to achieve high accuracy, we have installed a new Titanium Sapphire based light source. For this laser sources, we have measured the spontaneous emission hitting the atomic ensemble and put an upper bound of 10^{-18} on the resulting light shift.
- We have observed repeated accumulation of static electric charges on the vacuum system viewports on our two clock systems. Regular measurement of the DC Stark effect and

possibly discharge of static electricity with UV light is necessary.

Hg lattice clock

- We have implemented a new laser cooling source at 254 nm which largely increased the reliability and operability of the experiment.
- We have modified our lattice trap to allow deeper lattice depth at the magic wavelength of 362.5 nm. We can now access lattice depth of 56 E_R, 2.5 times more than previously.
- As a result of these improvements, we have improved by one order of magnitude the number of trapped atoms available, which in turn improved spectroscopy and clock operation
  - We have observed linewidth down to 3.3 Hz at 265.6 nm, which corresponds to an atomic quality factor of 3.5×10^{14}.
  - We have improved the short term stability to 1.2×10^{-15} at 1 second.
- We have improved our control of the main systematic shifts down to 10^{-16} which corresponds to a factor 50 improvement compared to our previous result (McFerran et al., Phys. Rev. Lett. 108, 183004 (2012)).
- We have performed new measurements against Cs and Rb fountains.
- We perform optical-to-optical frequency comparisons between the Hg optical lattice clock and a Sr optical lattice clock. This comparison shows stability of 3×10^{-15} at 1 s goes down to 5×10^{-17} at 3000 s.

5- Optical frequency metrology

Ultra-Stable Lasers

Laser stabilization based on spectral hole burning: We developed an experimental device aimed at realizing ultra-stable lasers locked onto narrow spectral features photo-imprinted in a rare-earth-doped crystal at cryogenic temperature (4K). This new technology has the potential to reach short term stabilities in the 10^{-17} or lower, due to the extremely low impact of thermal-agitation on the spectral features at cryogenic temperatures. We have demonstrated imprinting of spectral features narrower than 3 kHz (FWHM) and generation of an error signal suitable to servo a laser on them.

Other ultra-stable lasers: We maintaining and using ultra-stable lasers based on 10 cm long Fabry-Perot cavities at wavelengths of 1062.5 nm, 1542 nm and 698 nm with flicker noise floor ranging between 4×10^{-16} and 2×10^{-15}.

Optical frequency combs

Optical frequency combs were used for many absolute frequency measurements of 1542 nm, 1062.5 nm, 698 nm and 1160nm light against Cs fountains and measurements against FO2-Rb fountain. The measurement of the references of the laboratory at the first 3 wavelengths is now quasi-operational with >50% uptime over months and we have set up a continuous frequency lock of the 1542nm reference to the primary frequency standards of the laboratory.

We also investigated and developed a number of methods to generate extreme low noise microwave signals with Erbium fiber based optical frequency combs. This includes, in collaboration with industrial partners, the setup and characterization of new fiber-comb technologies with reduced intensity noise, use and characterization of new very high power handling and linearity photodetectors and repetition rate interleavers, and realization of phase noise measurement device with very low amplitude noise sensitivity. We can now generate microwave signals with phase noise at -165dBc/Hz at 100 kHz from a 12 GHz carrier.

6- Coherent optical links

Fiber links

This work is done in collaboration with LPL-Laboratoire de Physique des Lasers (CNRS and Université Paris 13) and RENATER, the French National Research and Education Network. We investigate frequency dissemination of an ultra-stable 1.5 µm optical carrier through the fiber network RENATER, using the so-called "dark channel approach", sharing fibers with internet data traffic. Regional and national (REFIMEVE) scale projects are under development and we are participating to European scale project that aim at connecting key laboratories with such coherent optical fiber links.

We implemented a cascaded optical link of 1420 km connecting SYRTE to University of Strasbourg through the RENATER network with parallel data traffic. This long haul fiber link comprises all the elements for future large scale deployment. This notably includes OADM for the chosen channel, bi-directional amplifiers, and four optical carrier signal regeneration stations. Relative frequency stabilities of 7×10^{-16} in 1-Hz bandwidth at one second and $<10^{-19}$ at one day are measured with this link. The accuracy of the link is evaluated to be $<1 \times 10^{-19}$.

Links from SYRTE and PTB (Physikalisch-Technische Bundesanstalt, Braunschweig, Germany) are now interconnected at University of Strasbourg, enabling optical frequency comparison by fiber links between the two metrology institutes. By operating simultaneously the two long haul links and the Sr clocks at SYRTE and PTB, we carried out the first international optical frequency comparison between distant optical Sr lattice clocks. The relative frequency stability of the comparison is about 2×10^{-15} at one second in 1 Hz bandwidth, and reach a statistical uncertainty $< 4 \times 10^{-17}$ in less than one day of operation.

A second international link of 800 km from SYRTE to NPL (National Physical Laboratory, United Kingdom) via LPL, in collaboration with PTB, is under construction on a dark fiber operated by GéANT, the European Research and Education Network.

Links in free space

This work is done in collaboration with OCA-Observatoire de la Côte d'Azur and ONERA.
We investigated the possibility of ground-to-space, and space-to-space transmission of a coherent ultra-stable carrier. In a first experiment, we implemented a horizontal, 5 km transmission of a 1064 nm optical carrier through the atmosphere in order to have a representative characterization of the phase noise introduced by turbulence. Next, we developed and characterized an agile ultra-stable laser system based on fiber spool delay line that allows compensating for the Doppler shift due to the satellite motion, which on the order of ±10 GHz. We have tried to establish a coherent link from the lunar laser ranging telescope at OCA to corner cubes on-board low Earth orbit satellites, without success. The reason is likely related to atmospheric turbulence and related issues of pointing and low return signal power. Presently we are carrying out extensive numerical simulations of the effects of atmospheric turbulence on such links, in collaboration with ONERA. This will allow a better understanding of the related limitations in satellite-ground coherent optical links.